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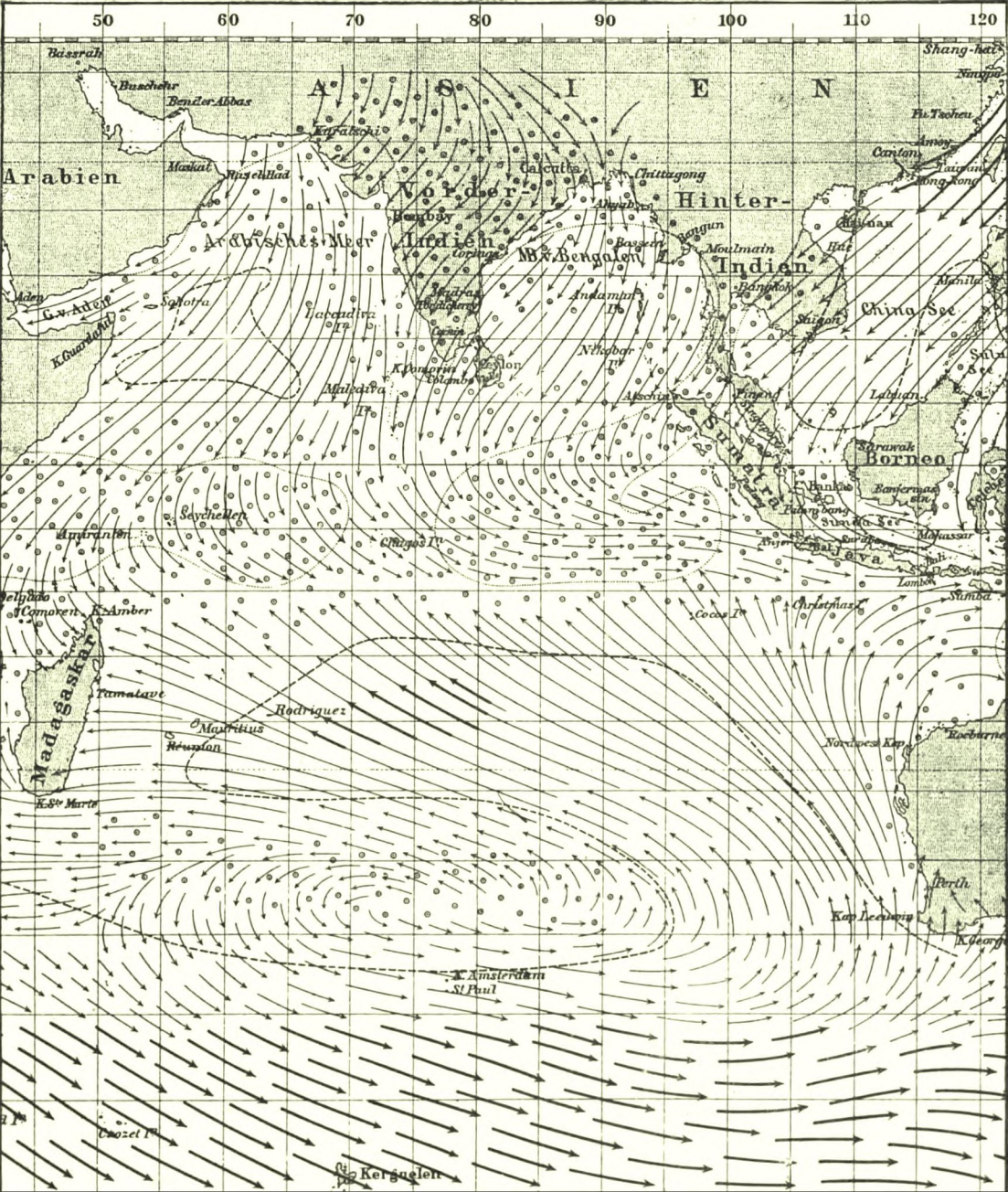

THE WINDS OF THE INDIAN OCEAN

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THE WINDS OF THE INDIAN OCEAN.

PROF. WILLIAM MORRIS DAVIS.

REPRINTED FROM THE AMERICAN METEOROLOGICAL JOURNAL, DECEMBER, 1893.

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THE WINDS OF THE INDIAN OCEAN.*

PROF. WILLIAM MORRIS DAVIS.

THE monsoons of the Indian Ocean are commonly referred to in illustration of the effect of a continent in disturbing the otherwise symmetrical arrangement of the trade winds; but according to the best modern charts, they illustrate also a peculiar deformation of the trade winds, independent of continental action, to which attention should be directed. This deformation is seen in the occurrence of a narrow belt of monsoon winds south of the equator, to which the name of terrestrial monsoons may be given, in distinction from the continental monsoons, north of the equator.

In articles on "A Classification of the Winds," published in this JOURNAL for March, 1888, and on "The General Winds of the Atlantic Ocean," in the JOURNAL for March, 1893, I have given a brief account of the general plan of a classification of the winds, which has been employed in my teaching for several years, and which appears to me more satisfactory, from being more natural and less empirical, than the classification usually employed, in which winds are classed as permanent, periodic, and variable. This simple and older plan is probably better suited, as many empirical methods are, to the practical man, who only wishes to use but not to enjoy his knowledge; but it does not satisfy the student, who employs a classification chiefly to aid him in looking into the natural relations of phenomena. In the classification referred to, a northward and southward migration of the several members of the general *planetary circulation*

* Read before the New England Meteorological Society in Boston, Oct. 21, 1893.

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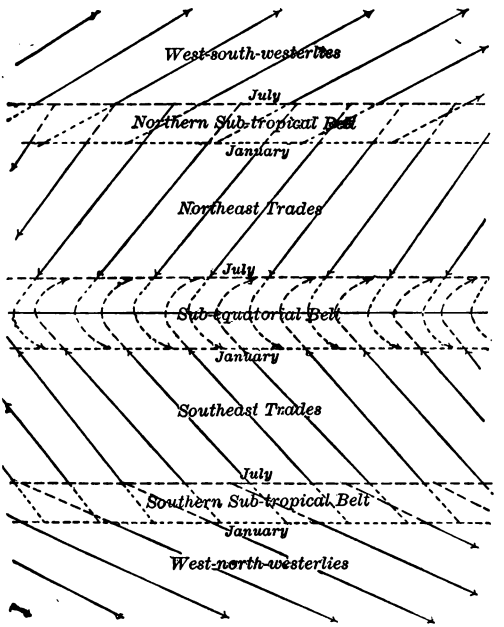
was presented as the chief characteristic of the circulation on our own earth, which was hence called the *terrestrial circulation.* I wish now to refer particularly to the effect of the migration of the doldrums on the winds of the sub-equatorial belt, across which the doldrums travel.

The accompanying diagram will make my meaning clearer. If the axis of the equatorial belt of low pressure remained fixed on the geographical equator, the trades would approach sym-



metrically from either side and fade away in the intermediate doldrums But when the doldrums pass to the north of the equator, in the late northern summer, the northeast trades are cut short, and the southeast trades are tempted to pass out of their proper hemisphere. They continue all the way on northward gradients, but they pass from a latitude in which an austral* deflection turns them to the left and enter a latitude in which a boreal deflection turns them to the right; thus the southeast trade of the southern hemisphere, swings around and becomes

* Following the terminology adopted for the aurora, I shall use the terms *boreal* and *austral* as referring to the northern and southern hemispheres.

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a southwest wind on our side of the equator. It may be called a monsoon wind, because in the opposite season this half of the sub-equatorial belt is occupied by the normal trade wind from the northeast. When the doldrums pass south of the equator in the late southern summer, a northwest monsoon wind should be formed by the extension of the northeast trade wind.

It should be noticed that these monsoons do not depend at all on the presence of continents; they are simply special features of planetary winds on an earth, whose axis is distinctly inclined from the vertical to its orbit, and whose year is long enough to cause a significant migration of its heat equator. It is not only true that continents are unessential to the development of these monsoons; they may even destroy the normal terrestrial monsoons. Such is the case in the South Atlantic, where the unsymmetrical outlines of Africa and South America require such an arrangement of ocean currents as to prevent the doldrums from moving significantly south of the equator. Hence there are no terrestrial monsoons in the South Atlantic. But where special disturbing influences are absent, terrestrial monsoons should be expected. Examples of their occurrence will be referred to further on.

On the other hand, where the location of continental areas, with respect to the geographical equator, is such as to tempt the belt of high temperature and low pressure to migrate over a great range of latitude, the alternation of the monsoon winds with the seasons becomes conspicuous. A series of monthly isobaric and isothermal charts, such as those prepared by Buchan for his "Challenger" report, should be consulted in order to determine where the heat and barometric equators migrate to land areas at exceptionally great distances north or south of the geographical equator, as well as to determine their migration under normal terrestrial conditions. The north and south migration of the heat equator following the sun is strong over Africa, and there we might expect well-marked examples of continental monsoons on both sides of the equator; but in the interior of the dark continent, the winds are little studied. The migration is strong to the north upon India in our summer; and distinct to the south over Australia in the summer of the southern hemisphere; in both of these regions, monsoons should be unsymmetrically developed in northern and southern lati-

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tudes. The migration is moderate to the south on the open Indian Ocean between Africa and Australia; there a moderate development of purely terrestrial monsoons should be expected; and these taken with the continental monsoons of the adjacent lands make the Indian Ocean of special interest in studying this subject.

Before examining the modern maps of this ocean, let us briefly refer to two older accounts of its winds. We may quote from Dampier, the old navigator, who wrote about 1700; and from Capper, an officer of the East India Company, who wrote about 1800.

Old Dampier tells us, after speaking of the shifting trade winds in the Red Sea, that: "From Comorin, clear round the Bay of Bengal, the change is no less; and even from thence, through the Streights of Malacca, and eastwards as far as Japan, the shifting trade winds do alternately succeed each other as duly as the year comes about." All round the Bay, the winds "shift in the shifting seasons, which are April and September, at one and the same time, to their opposite points: I mean on the open coast, for in some bays there is a little alteration from that general rule. These shifting winds in the East Indies are called monsoons; one is called the east monsoon, the other the west monsoon. The east monsoon sets in about September and blows till April, then ceaseth; and the west monsoon takes place and blows till September again. . . . The east monsoon brings fair weather; the west brings tornadoes and rain. For . . . when the sun comes to the north of the line, then all places north of the equator, within the tropics, are troubled with clouds and rain, but when the sun is in southern signs then the sky is clear. . . . And tho' these winds do not shift exactly at one time in all years, yet September and April are always accounted the turning months, and do commonly participate of both sorts of winds. . . . For these monsoons do as constantly shift by turns, as the year comes about. And by means of this change of wind, ships have the benefit to sail from one part of India, with one wind, and return with the contrary: so that most of the navigation in India depends on the monsoons. And ships do constantly wait for these changes; and the merchants fit out to any place according as the season of the year draws on: And wheresoever they go, they certainly dispatch their business so

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as to return back again with the next or contrary monsoon: for here is no sailing to and from any place but with the monsoon; one carries them out, the other brings them back." (Dampier's "Voyages," London, 1705, Vol. II., Part iii., 20–23.)

Dampier's rough charts of the winds represent a constant trade wind for the greater part of the South Indian Ocean within the torrid zone; but north of the equator all along the southern and eastern coasts of Asia, up to Formosa, paired arrows in opposite directions are drawn to indicate the alternating monsoons.

Capper's account of the monsoons is not very explicit as to times and places of occurrence; but he introduces mention of a feature to which Blanford later gives prominence; namely, the deflection of the wind in certain districts from its ordinary course. His statement on this point is as follows: "In tropical countries there are but two seasons: those in Hindustan are distinguished by the northeast and southwest monsoons. But farther to the eastward and southward of the line, and the Gulf of Bengal, the monsoons blow from different quarters. The northeast becomes in those parts the northwest and the southwest becomes the southeast." ("Observations on the Winds and Monsoons," London, 1801, 40, 41.) It is not plain whether Capper here refers to the deflection of the monsoon winds up and down the plain of the Ganges; but he seems to refer certainly to the austral deflection of the winds south of the equator. His essay has no map of the winds, and his text is not perfectly clear. Giving him the benefit of the doubt, it appears that in the above brief sentence we have the first recognition of the facts to which I wish to give special emphasis in this essay.

It may be noted in this connection that Capper is most frequently referred to nowadays as one of the earliest authors to recognize the whirlwind character of the cyclones of the Bay of Bengal, to which he devotes a number of pages. He does not describe their winds very clearly, nor does he specify the direction of their vorticular rotation; but in trying to explain their cause, he seems to adopt a suggestion of Franklin's in ascribing small whirls to ascending currents, and larger storms to the descent of unduly cooled and heavy air from the upper regions of the atmosphere. Then "the parts adjacent will immediately concentre to a point, and rush with a whirling circular motion

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towards the bottom with great violence. . . . It would not, perhaps, be a matter of great difficulty to ascertain the situation of a ship in a whirlwind, by observing the strength and changes of the wind. If the changes are sudden and the wind violent, in all probability the ship must be near the centre or vortex of the whirlwind; whereas, if the wind blows a great length of time from the same point, and the changes are gradual, it may be reasonably supposed the ship is near the extremity of it." (*Ibid.*, 65, 66.)

As stated at the beginning of this essay, modern writers seldom make mention of the austral deflection experienced by the northeast trade, when it crosses the equator and enters the southern hemisphere as a northwest wind. Let us, therefore, next examine the best recent chart of this ocean, and see how it presents the facts.

The facts of the case, without regard to classification or theory, but generalized on the basis of the fullest possible collection of observations, are best represented in two maps here reproduced from the Atlas of the Indian Ocean, in chief part prepared by Dr. W. Köppen, and published by the German Marine Observatory, at Hamburg.*

Chart I is for January and February, the late summer of the southern hemisphere, when the heat equator and the belt of low barometric pressure have advanced to about latitude 10° S., in the middle of the Indian Ocean. The heavier arrows show stronger winds; the longer arrows, steadier winds. On this chart, the southern tropical belt of high pressure is broken on the warm lands of Africa and Australia, and a flattened but distinct anticyclonic system of outflowing winds is seen around the localized oval area of high pressure midway between Australia and South Africa. All these features of temperature and pressure, as well as of winds, are finely exhibited by special charts in the atlas referred to above. South of the anticyclone, we see the strong west-northwest winds, forming a part of the

* Indischer Ozean. Ein Atlas von 35 Karten. Beilage zum Segelhandbuch für den Indischen Ozean. Deutsche Seewarte, Hamburg, 1891. The Segelhandbuch gives a full account of the winds. In my reference to the similar maps in the atlas of the Atlantic Ocean, in the JOURNAL for last March, I should have mentioned the name of Dr. Köppen, as the meteorologist chiefly responsible for the preparation of the charts.

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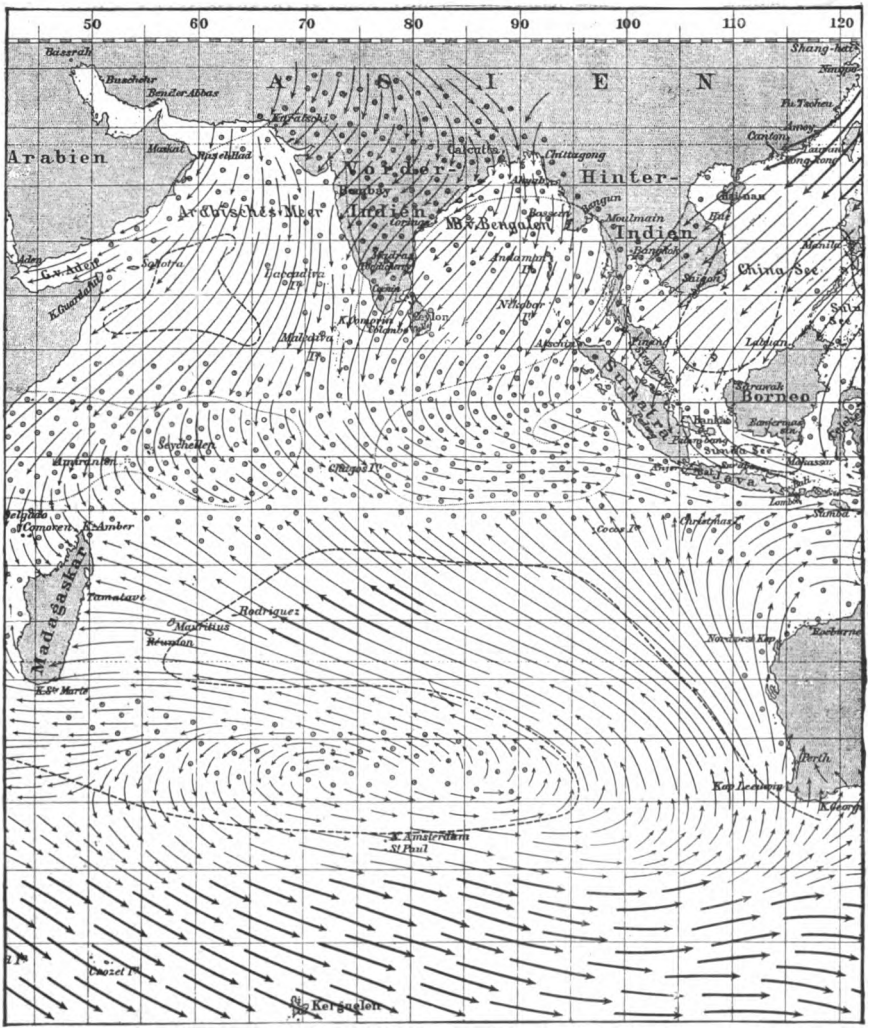

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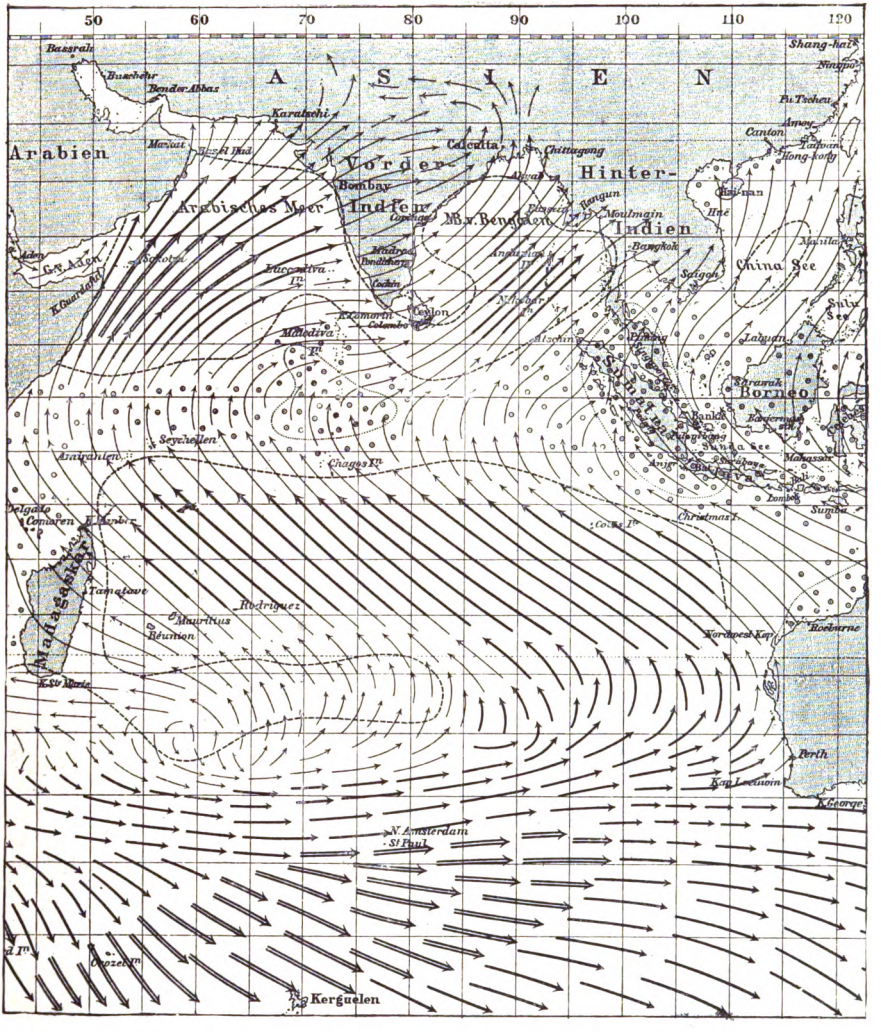

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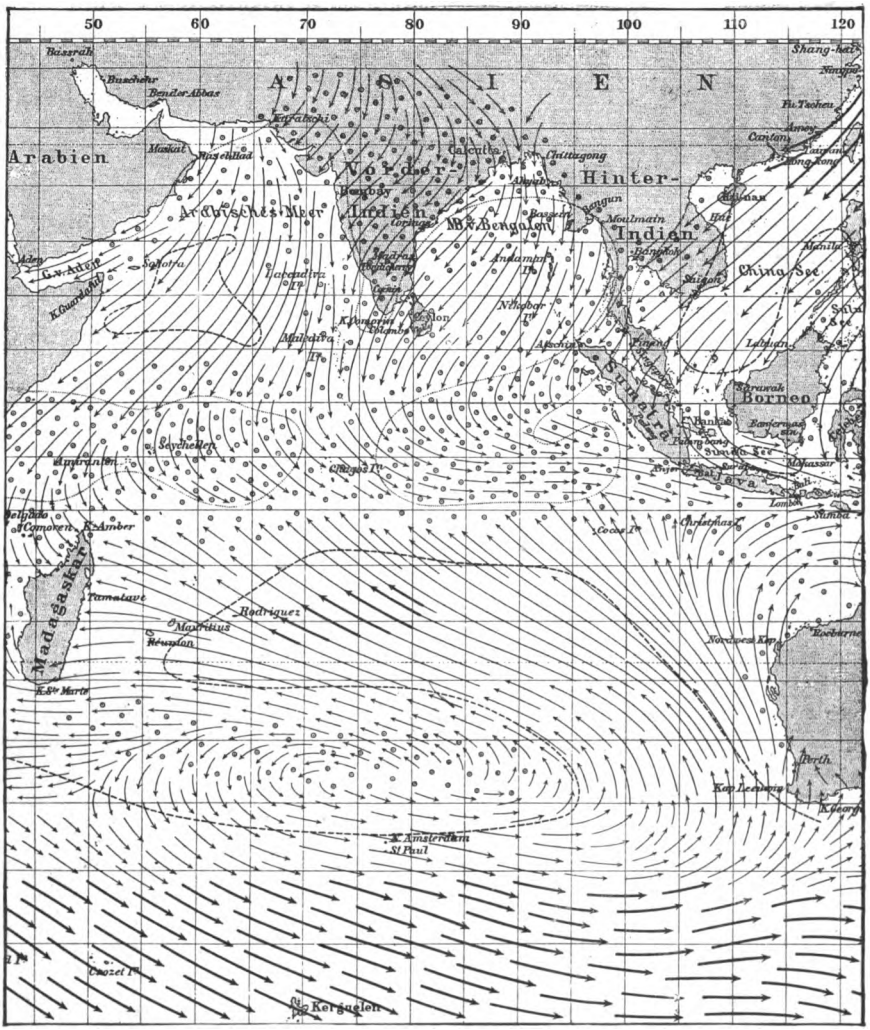

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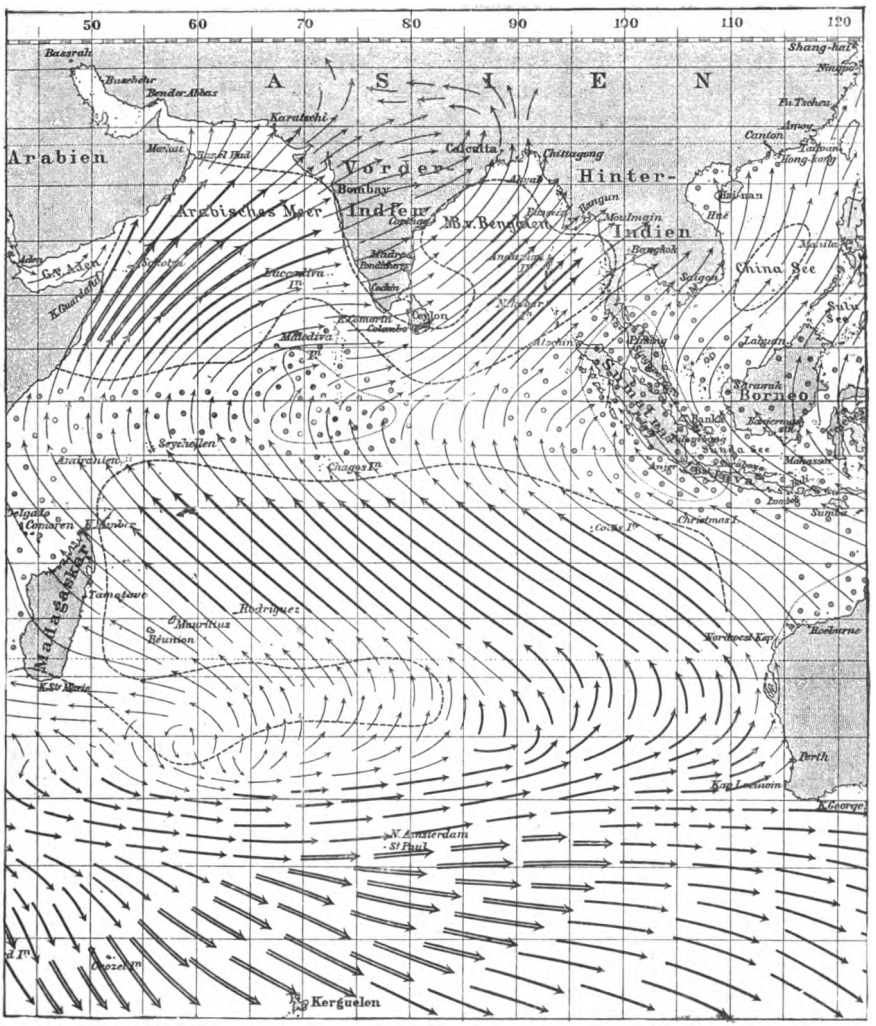

WINDS OF THE INDIAN OCEAN. — JULY, AUGUST.

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great whirling circulation around the south pole; north of the anticyclone flow the trade winds, normally from the southeast, but locally deflected to a more southerly course near Australia, and a more easterly course near Africa. North of the equator, the northeast trade blows with much regularity over the waters; its strength being greatest on the western Pacific, and least over the peninsula of India, where, as Blanford points out, the windmill has not been employed in pumping water in the dry season, although the natives have had sufficient ingenuity to invent other mechanical devices for use in irrigation. The weakness of the wind there is primarily due to the faintness of the gradients which cause it; secondarily, to the obstruction offered by the inequalities of the land surface; and finally to the absence of local convection in the cooler season, by which the surface and overlying currents may be mixed and a greater velocity given to the wind close to the ground. The course of the northeast monsoon is significantly deflected on certain parts of the peninsula and in the great gulfs on either side, — the Bay of Bengal and the Arabian Sea, — so that Blanford advises that it should be called the winter monsoon. In Bengal, it comes from the northwest; west of Bombay, it comes from the north. All of this is, however, aside somewhat from the chief interest of the map.

As the barometric equator lies ten degrees south of the geographic equator, the northeast trade wind does not stop at the latter limit; but passes into the southern hemisphere; and then promptly swings around and becomes a northwest wind. This is probably the "N.W." that Capper described as occurring "southward of the line." Approaching Java, this wind advances almost directly eastward, to take part in the austral cyclonic inflow or continental monsoon over Australia; while near Africa, it comes from the north, or even maintains its northeast source, on its way towards the heated interior of that continent.

It is manifest that the northwest wind, south of the equator in the middle of the Indian Ocean, is a purely terrestrial product; as such, it is the best example of its kind yet charted. In the Atlantic, the form of the continents and the consequent course of the ocean currents, taken with the comparative narrowness of that ocean at the equator, prevents the development of a

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distinct monsoon wind in mid-ocean ; although near the African coast, north of the equator, a hybrid monsoon, partly terrestrial, partly continental in origin, is seen in the northern summer. In the Pacific, there is breadth enough ; indeed, too much for successful study at this date. The expanse of waters is there so vast, and the observations are relatively so few, that our knowledge of that ocean is not yet sufficient for the construction of maps like those which now so well illustrate the meteorological features of the Atlantic and Indian oceans ; but of this more, below, in connection with some remarks on currents.

Turning now to the second chart, representing the average winds for July and August, we may first note a general increase in velocities over the Indian Ocean, and a decrease over the Western Pacific. The increase over the Indian Ocean is due, in the southern hemisphere, to the increased strength of the circumpolar gradients ; and in the northern, to the excessively high temperatures in Northwestern India. In examining the directions of the wind, there is little change to be noted in the southern part of the ocean. The division between the westerlies and the southeast trade is somewhat more linear than before ; because the tropical belt of high pressures is now less interrupted on the lands than it was in the southern summer ; but there is still a well-marked northward branching from the westerlies into the trade along the western coast of Australia. The position of the high pressure belt is about five degrees more northward than before ; this being a consequence of the increased velocity of the circumpolar whirl, as was described in my former paper. Anticyclonic outflows of air now appear over Australia, and to a less degree over Africa also, as these lands are now centres of relatively low temperatures, being cooler than the surrounding seas.

The extension of the southeast trade wind across the equator, as the southwest or summer monsoon, is the most striking feature of this chart. The obedient manner in which this vast current of air changes from an austral to a boreal habit of deflection, on passing from one hemisphere to the other, is nothing less than admirable. How anyone can question the sufficiency of the rotation of the earth to influence the course of the winds in face of such facts as these is really mysterious. The southern half of the torrid zone is occupied, over the open ocean, by a

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normal trade wind of much strength and remarkable constancy, both in direction and persistence; the northern gulfs of the ocean have as strong and as steady a wind, but it comes from the southwest; yet in both cases the wind moves on northward gradients. The belt of weaker and less constant winds, with not infrequent calms along the equator, is seen, by comparison with the chart of temperatures, to result from a belt of weak temperature gradients, and hence weak barometric gradients; these being the representative of the extinguished doldrums, now supplanted by the belt of low pressure in Southern Asia. In this connection, it may be noted that the development of the terrestrial monsoon in the southern hemisphere, and of the continental monsoon in the northern hemisphere, are unlike in a certain respect. The southward advance of the doldrums from the equator to their most southern position, where they stand in January or February, is accomplished by a steady migration; and the inflowing trade wind, deflected according to the hemisphere that it occupies, simply follows this migrating belt of high temperature and low pressure. But when the sun moves north and the doldrums start after it, there is no such regularity of migration all the way to the northern position of the summer belt of low pressure. When the doldrums have returned to the equator in April, the rise of temperature over Northern India becomes so rapid that the seat of highest temperatures and lowest pressures is, as it were, at once transplanted to latitude 25° north; and then the winds are no longer satisfied on reaching the doldrums, but blow onward to this new goal. The former position of the doldrums is then marked only by the belt of weaker winds and occasional calms along the equator, as already mentioned. Five or six months later, the belt of low pressure is transplanted from its abnormal position on Northern India to the true doldrum belt; and then the regular southward migration is established.

The deflections of the monsoon on reaching India are as noticeable as were those of its predecessor six months before. It blows almost from west to east across Southern India; while over the plains of the Ganges it is a southeast wind. Hence, as far as the peninsula is concerned, it had better be called, again following Blanford, the summer monsoon, after its season, and not the southwest monsoon.

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In view of all these facts, it seems not too much to say that any account of the monsoons of the Indian Ocean is incomplete if the terrestrial monsoons of the southern hemisphere are omitted. Although less famous, less conspicuous, and less important in their practical relations than the continental monsoons, they deserve careful recognition by the student of meteorology.

A brief postscript is suggested concerning the currents of the Indian Ocean. It is interesting to notice that even at the time of Dampier's voyages, the relation of the currents around India to the monsoons had been noticed. He says: "On the coast of India, north of the line, the current sets with the monsoon, but does not shift altogether so soon, sometimes not by three weeks or more, and then never shifts again till after the monsoon is settled in the contrary way. As, for example, the west monsoon sets in the middle of April, but the current does not shift till the beginning of May; so when the east monsoon sets in about the middle of September, the current does not shift till October." ("Voyages," Vol. II., Part iii., 107.)

The relation of cause and effect between winds and surface currents thus appears to have been clearly brought out two hundred years ago.

In another respect, these currents are of peculiar interest. All the great oceans possess eddy-like currents, turning from left to right in the northern hemisphere; and from right to left in the southern. The equatorial members of each eddy, therefore, advance from east to west, and might work closely together, if it were not for the equatorial counter currents, which in both the Atlantic and the Pacific more or less completely separate the adjacent members of the normal eddies. The counter current of the Pacific is always represented somewhat north of the equator; and I suspect that its best development will be found to be in the late northern summer, when a terrestrial monsoon appears to occur just north of the equator in the Pacific; but we have little information on this point. The counter current of the Atlantic, commonly called the Guinea current, lies distinctly north of the equator, increasing in length in our summer, when the hybrid southwest monsoon of that region has its greatest development.* In confirmation

* The Winds and Currents of the Equatorial Atlantic. Amer. Met. Journal, I., 1884, 53, 54.

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of the explanation that refers the equatorial currents to the monsoon winds near the equator, we may look at the special arrangement of the currents in the Indian Ocean.

When the sun is north of the equator, and the southwest monsoon is produced, there is a strong eastward current along the northern border of the ocean; it is irregular on account of the uneven form of the ocean's outline, but as it moves eastward within the torrid zone, it may be called a counter current. South of the equator, the normal right-to-left eddy wheels around in its everlasting circuit.

When the sun is south of the equator, and the narrow terrestrial monsoon is blowing from the northwest across the southern sub-equatorial belt, there is a counter current formed beneath it, while the northern part of the ocean is occupied by a current moving westward, and thus simulating the equatorial portion of a boreal eddy. The semblance is imperfect, for this westward marginal current joins forces with the equatorial counter current, and the two make an eddy turning in the wrong direction, and not in gear with the eddy of the southern hemisphere.

So far as the comparison goes, it is not unfair to say that in this ocean, where monsoons are developed on both sides of the equator, according to the season, the counter currents also occur on both sides of the equator, accordant with the winds. The Atlantic and Pacific have the monsoon element only north of the equator; and their counter currents inhabit only the northern hemisphere, close to its border. The Indian Ocean has a better developed monsoon system, now on one side of the equator, now on the other; and the position of its counter current also oscillates from the northern to the southern side of the line.

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